North American Spine Society Journal (NASSJ) 20 (2024) 100548

Contents lists available at ScienceDirect

North American Spine Society Journal (NASSJ)

journal homepage: www.elsevier.com/locate/xnsj

Pediatric spinal alignment and spinal development

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ARTICLE INFO

Keywords:
Sagittal alignment
Pediatric spinal growth
Adolescent idiopathic scoliosis (AIS)
Pelvic incidence
Skeletal maturity classifications

ABSTRACT

Background: Knowledge of the growth spurt and remaining growth is essential for managing musculoskeletal diseases in children. Accurate prediction of curve progression and timely interventions are crucial, particularly for conditions like adolescent idiopathic scoliosis (AIS).
Methods: This study conducted a comprehensive review and synthesis of existing literature on spinal growth, skeletal maturity classifications, and the evolution of sagittal alignment parameters during childhood and adolescence. Key anatomical elements involved in spinal development, natural history of spinal growth, and skeletal maturity assessment systems were analyzed.
Results: The analysis highlighted that key parameters such as Pelvic incidence (PI), Pelvic tilt (PT), and Lumbar lordosis (LL) increase significantly with growth, especially during the pubertal growth spurt. In contrast, Sacral slope (SS) remains relatively constant, and Thoracic kyphosis (TK) shows a slight increase. Additionally, there is a posterior shift in the center of gravity as children grow, reflecting progressive postural maturation. The study also reviewed and compared various maturity classification systems, noting the reliability and clinical implications of systems like the Sanders Maturity Stage (SMS) and Tanner-Whitehouse III.
Conclusions: Reliable maturity classification systems, such as the Sanders Maturity Stage (SMS) and Tanner-Whitehouse III, allow for tailored treatments to individual growth patterns. Integrating these classification systems into clinical practice enables precise prediction of curve progression and timely therapeutic interventions. This includes options from bracing to surgical techniques like growing rods or vertebral body tethering (VBT), with growth modulation being a key factor in achieving successful outcomes.

Introduction

Knowledge of the growth spurt and the remaining growth is essential for the management of musculoskeletal diseases in children. Continuous harmonization of spinal sagittal alignment is necessary in children to support their postural, functional and pulmonary developments. Spinal deformities therefore require specific management strategies during growth, while curve progression should also be accurately predicted until skeletal maturity in idiopathic scoliosis (IS). Thus, therapeutic strategies go from simple surveillance to orthopedic (brace) and/or surgical treatment [1–4]. Physicians must be familiar with the different landmarks of maturity in adolescent idiopathic scoliosis (AIS) to predict the potential progression of the deformity and thus propose the most appropriate treatment. Me Duval-Beaupère was the first physician to clearly describe the link between growth velocity and spinal curves progression and all the further classification and evaluation systems were based on her principles and correlate skeletal growth with the peak height velocity (PHV) [5]. These are essential to choose the best therapeutic window for medical or surgical treatment in AIS, since scoliosis progression during adolescence is closely related to skeletal maturity [6].

Different parameters allow to evaluate maturity in adolescent: the civil age, the age of menarch, the height and weight, the sexual and skeletal maturity [7]. Several classifications, based on bony landmarks exist such as the Risser classification, the Oxford Hip maturity system, the Greulich and Pyle method and the Tanner-Whitehouse scoring. The Risser classification is the most commonly used but has been demonstrated to be inaccurate to predict the PHV and the residual spinal

FDA device/drug status: Not applicable.

Author disclosures: ***LSC***: Nothing to disclose. ***ALS***: Nothing to disclose. ***MK***: Stock Ownership: Novaspine (Level B). ***EF***: Consulting: Medtronic (Level B); Speaking and/or Teaching Arrangements: Implanet (Level B); Trips/Travel: Implanet (Level B), Medtronic (Level B), Spineart (Level B).

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https://doi.org/10.1016/j.xnsj.2024.100548
Received 29 June 2024; Received in revised form 8 August 2024; Accepted 9 August 2024
Available online 13 August 2024

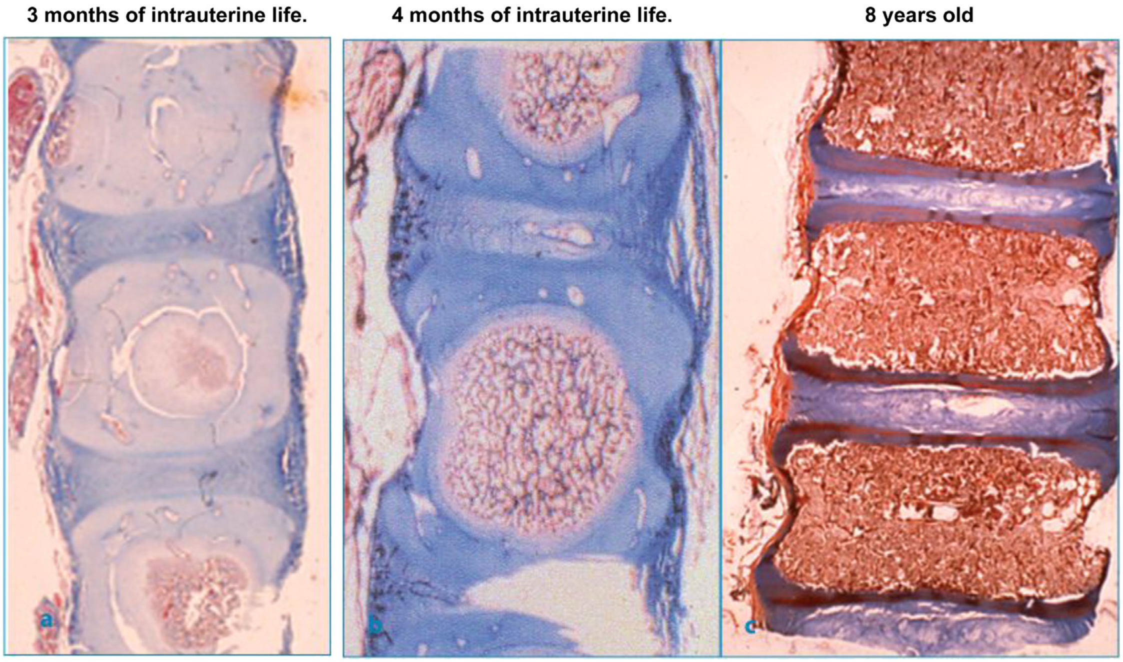

Fig. 1. The evolving morphology of the vertebral body: (A) at 3 months of intrauterine life, (B) at 4 months of intrauterine life, (C) at 8 years.

growth scoliosis progression [8]. Therefore more sensitive scaling systems were developed [9–11]. Tanner developed the Tanner-Whitehouse III scoring system based on the epiphysis ossification of the hand, the radius and the ulna, that is particularly difficult to use in daily practice [12]. Based on the Tanner-Whitehouse system, Sanders developed a simplified scoring: the Sanders Maturity Stage (SMS) which is more accurate to predict PHV and the growth potential [13]. The combined analysis of initial curve magnitude and SMS rating allows a more precise estimation of the curve progression and thus a patient specific therapeutic strategy for AIS treatment [14–16].

This paper aimed to explain the anatomic elements involved in the spinal development and the natural history of the spinal growth. The main skeletal maturity assessment systems and their clinical implications will also be reported as well as the characteristics of spinal sagittal alignment in children.

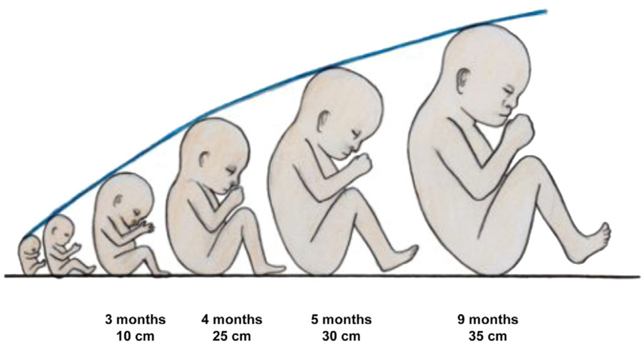

Fig. 2. The vertebra - coccyx length.

Anatomical considerations

Spinal growth is complex and differs at each level [17,18]. A total of 130 growth cartilages exists, each component growing independently but with an organized harmony based on a rigorous timeline. The spine has 3 main periods of growing (Fig. 1): (1). The embryonal period (< 3 months of pregnancy): the elements get organized. The vertebral contour and the spinal cord are developing. The first 2 months are decisive because of the somite migration, the sclerotic differentiation of the sclerotomes and the closure of the posterior arch, which is linked to the closure of the medulla, around 6 weeks in utero. (2). The fetal period (>3 months pregnancy): the spine gets ossified. (3). The after-birth period: the ossification continues and 2 important growth periods exist: the 0–5 years period and the puberty. Spinal growth ends around 18–25 years old.

Fetus

During the fetal period, spinal growth is very important. At 2 months, spine length corresponds to 2/3 of the child size and to 3/5 after 5 months of pregnancy (Fig. 2). A cartilage matrix gradually replaces the mesenchyme (Fig. 3). Then, ossification fronts rapidly appear in the left and right posterior arches and the anterior vertebral bodies within the cartilage matrix. The ossifications appear first in the dorsal region, and progress further to the lumbar and the cervical regions.

The spine is essentially straight or with a slight forward concave curve in the first intrauterine 3 months. At 5 months, the sacro-vertebral angle emerges, establishing the line between the lumbar and the sacral region, but the inflections points of the cervical and the lumbar region are still not visible.

Child

At birth, the spinal cord length corresponds to 2/5 of the child size, but only 30% of the spine is ossified. Vertebrae had 3 ossifications points: one in the anterior part of the body and 2 for the right and left posterior arches. Vertebral bodies have a centripetal growth, the growth plate (the Listel marginal cartilaginous nodes) being around the anterior vertebral body allowing the growth of the superior and inferior endplates in thickness and in height.

During this period, 2 important phenomena exist: the psychomotor development with neuromotor learning and the growing truck height while sitting, which directly reflects vertebral growth.

The first year of life is dominated by 2 events: the development of the bone marrow, which adjusts to the spine and the formation of the 3 sagittal curves. At birth, the spine is globally kyphotic and the cervical

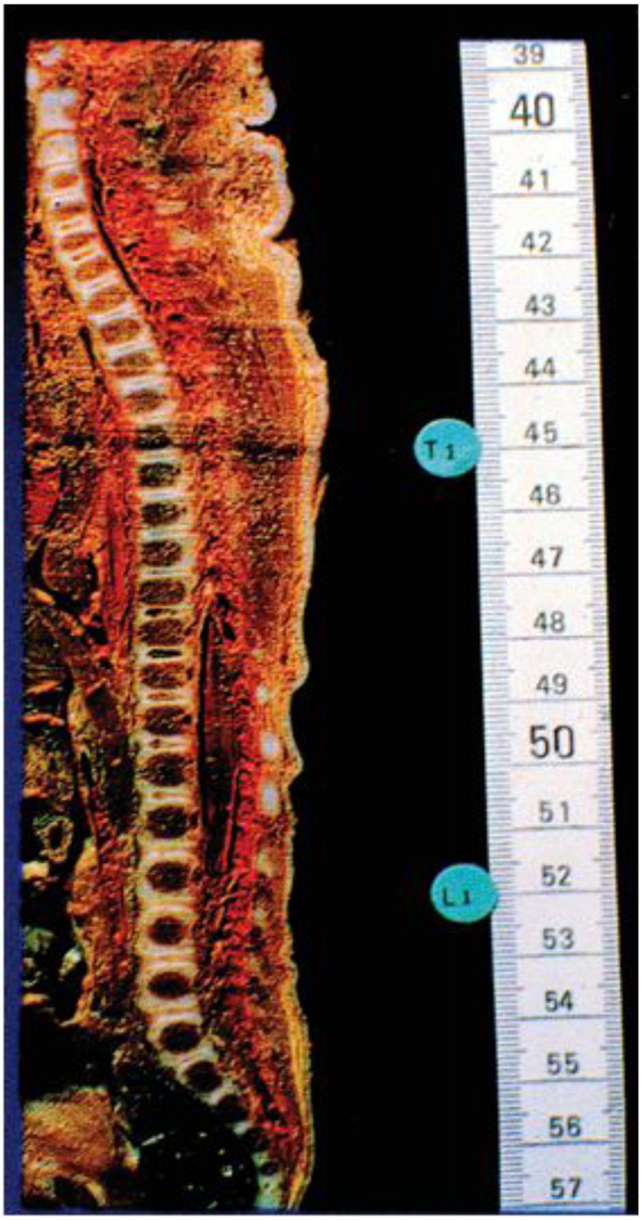

Fig. 3. Sagittal section of the spine at 8 months. Ossification initially occurs dorsally; it then extends radiantly upward and downward.

lordosis (CL) appears first due to the head and trunk control development (vision, 4 legs walking). The lumbar lordosis (LL) appears finally when the child starts to stand and walk (Fig. 4).

Growth during this period is strong. Mean trunk height in the first year is around 12 cm. In the first year of life, sitting height then rises from 35 to 47 cm. From 1 to 5 years of age, the gain in sitting height is 15 cm; sitting height increases from 47 to 62 cm. This growth spurt in the first 5 years of life is even stronger than during puberty (12–14 cm). At the end of growth, spinal length almost triples. Spinal growth decelerates between 5 years and beginning of puberty.

Spinal growth at puberty

Growth spurts started around 11 years-old and 13 years-old in respectively girls and boys. Mean trunk growth is of 12 cm and 13 cm respectively with 2 years of high growth velocity between 11 and 13 years old in girls (mean of 7cm) and 13 and 15 years-old in boys (mean of 8 cm).

The growth slows down after elbow growth endplate closure.

It is crucial to determine the time of the peak height velocity (PHV), as it is a strong prognostic factor of progression in children with idiopathic scoliosis [19,20]. It is identified through serial height measurements and growth velocity calculation. Sanders observed that the curve acceleration phase correlates better with the timing of the peak height velocity than with the onset of the growth spurt [7]. This reinforces the idea that instability linked to rapid growth during this period is one of the mechanisms of scoliosis progression [21,22].

In the 80′s, Duval Beaupère was one of the pioneers to describe the rules of IS progression [5]. She observed that single thoracic or double major curves were more at risk of progression during puberty in a population of 159 mild AIS (<30° main Cobb angle), as well as nonreducible Cobb angle in supine position and major thoracic bump. The curves progression, based on spinal growth and occurrence of puberty and scoliosis evolution related to the age at onset were resumed by her on a graph: mild curves (<30°) evolve slowly in 80% whereas the remaining 20% will require surgery (Fig. 5).

Skeletal maturity classifications

The Risser classification

In 1936, Risser observed that the ossification of the iliac apophysis was correlated with spinal growth. Subsequently, Lonstein and Carlson demonstrated an association between the progression of scoliotic curves and the different stages of the Risser classification, age, type of scoliosis and the pubertal status [23]. Thus, the evaluation of skeletal maturity in scoliosis provides information for treatment regarding brace duration or surgical indication. The Risser sign has therefore become a widely used tool to understand skeletal maturity and the risk of scoliosis progression [24,25].

However, even though the Risser classification is frequently used to determine skeletal maturity in patients with IS, it is poorly correlated to the worsening of the curvature point and has several limitations [7]. First, iliac crest ossification starts at Risser 1 which is after a mean of 18-months after the growth spurt starts. Most of scoliosis curves progression is therefore before Risser 1. Moreover, progression from stages 1–4 occurs with a 1 single year [19]. Secondly, Izumi et al. observed that the appearance of the iliac apophysis on postero-anterior radiographs does not correlate well with anteroposterior radiographs because of the parallax effect of the X-ray beam [26]. Third, 2 versions of the Risser grading scale are available (US and French) [27,28]. Both have 6 grades to assess spinal growth, but the United States version divides the iliac crest into quarters, and the French version divides it into thirds (Fig. 6) after Risser III stage.

Greulich and Pyle method

The Greulich and Pyle Atlas provides an excellent radiographic illustration of the different stages of bone maturity and is easily available. However, it was developed from X-rays representing children of different civil ages without considering clinical criteria which may be linked to PHV such as secondary sexual characteristics which are now considered important markers of maturity.

Indeed, the onset of PHV in adolescents can vary significantly, with a variability of up to 4 years for the beginning of the growth spurt [29]. Sanders and Tanner agreed to say that the concept of skeletal maturity was more appropriate than the concept of bone age and preferred a system that did not only rely on age at X-rays [12].

Tanner-Whitehouse

The Tanner-Whitehouse III RUS method (radius, ulna and small bones of the carpe) specifically uses the ossifications points from the radius, the ulna, the metacarpal bones and the first, third and fifth fingers phalanges to determine the skeletal age [12,30]. Each ossified bone

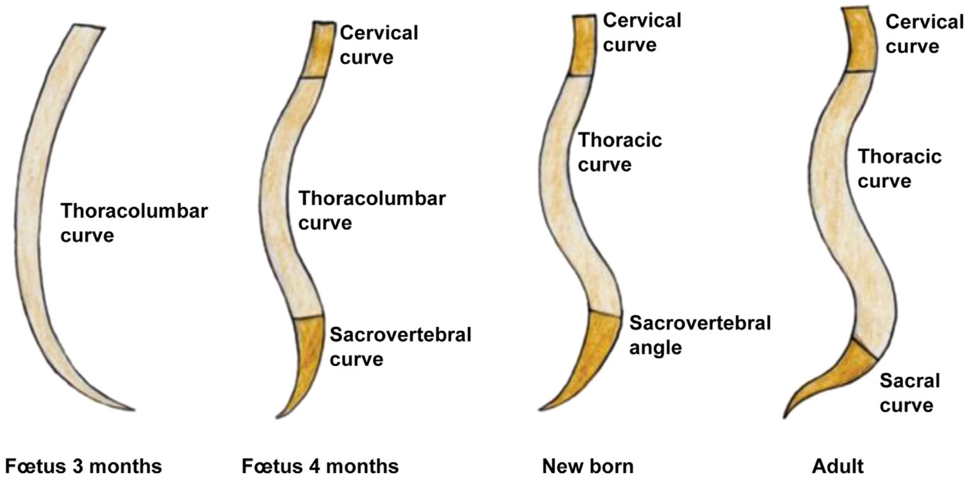

Fig. 4. Evolution of spinal curvatures: 3-month fetus with a large "C" shaped curve; 4-month fetus showing the emergence of the sacro-vertebral angle; from birth to 1 year, curvatures develop with neurological milestones, including cervical lordosis, thoracic kyphosis, and lumbar curvature.

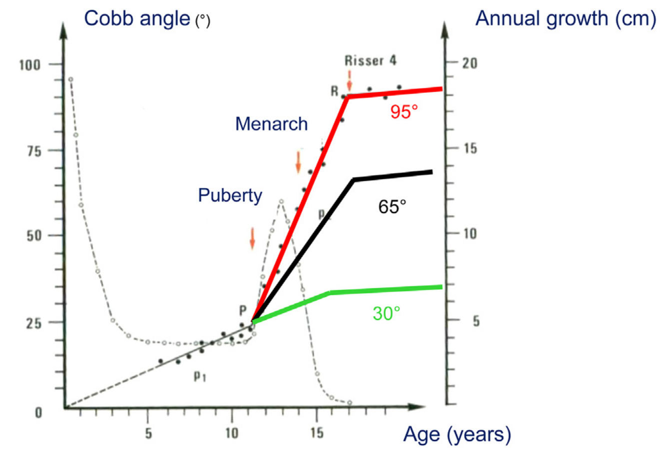

Fig. 5. Duval-Beaupère graph showing the evolution of the Cobb angle (degrees) with growth (cm) and age (years).

is associated with a maturity score. Then, all scores are added together to obtain the total RUS score. If RUS method is much more correlated with periods of scoliosis acceleration, it is nevertheless very difficult to use because it requires having the Tanner-Whitehouse atlas III to calculate the score.

Sanders and al., showed that the ossifications of the distal radius and distal ulna epiphysis had poorer correlations than the phalangeal epiphyses with scoliosis and spinal growth progression and proposed a simplified version of the Tanner-Whitehouse III method.

Sanders maturity stage

This classification is based on antero-posterior hand radiographs with 9 different stages (0–8) of maturity (Fig. 7) [14]. (0). The infantile rapid stage (stage 0) occurs between 0 and 5 years old. (1). The juvenile slow stage (stage 1) occurs before the beginning of the adolescent growth spurt. All digital epiphyses are not covered, and secondary sexual characteristics are Tanner stage 1. (2). The preadolescent slow stage (stage 2): the adolescent growth spurt has started but it is before the PHV; all digital epiphyses are covered and secondary sexual characteristics are Tanner stage 2. (3). The adolescent rapid stage-early (stage 3): the scoliosis curves start their acceleration phase and is the time of the PHV; the preponderance of the epiphyses cap their metaphyses and secondary sexual characteristics are Tanner stage 2 or 3. (4). The adolescent rapid stage-late (stage 4): scoliosis curves increase rapidly; one or more of the distal phalanges physis start to close and secondary sexual characteristics are Tanner stage 3. It corresponds to Risser 0 stage and triradiate cartilage are still open. (5). The adolescent steady progression stage-early (stage 5): all distal phalangeal physes are closed (Tanner-Whitehouse-III stage I) whereas the proximal phalangeal physes are still open; girls are still in Risser stage 0, but triradiate cartilages are closed. (6). The adolescent steady progression stage-late (stage 6): proximal and middle phalangeal physes are nearly closed; the Risser sign is usually positive and menarche usually occurred in girls. (7). The early mature stage (stage 7): scoliosis progression can still occur; only the distal radial physis is open and it usually corresponds to Risser stage 4. (8). The mature stage (stage 8): Risser stage 5 and end of growth. The key feature of this stage is that the distal radial physis is completely closed.

Thus, SMS 3 is crucial to be identified because it is the beginning of the growth spurt [14]. Since PHV is difficult to be accurately predicted, a subclassification was developed: SMS 3A et SMS3B [31]. In a recent study, Hori et al. observed that most of patients in SMS 3A were Risser 0 with open triradiate cartilage and premenarchal for the girls, whereas SMS 3B included mixed Risser and triradiate cartilage stages with 30% of menarched girls [1]. SMS 3 subclassification is of utmost importance to adapt scoliosis treatment to the patient growth, with observation, bracing, or surgery. Authors concluded that patients with a 20° Cobb at SMS 2 or a 30° at SMS 3 are at high risk of progression even with bracing [1].

Other authors analyzed Sanders and Risser reproducibility. Inter- and intraobserver reproducibility analyses showed that the Sanders had moderate reproducibility on young fellows but a good one on attending doctors. On the other hand, it was found that Risser reproducibility was worse whatever the category of the doctor was [6].

Proximal humerus ossification

A more recent classification has been developed and based on the humeral head ossification, which is easily accessible on full-spine radiographs (Fig. 8). It is a 5 stages classification based on the development of the humeral epiphysis and its fusion from medial to lateral margin [32]. These 5 stages were well distributed during the growth period to predict the PHV and correlate with the growth spurt. This study also demonstrates a good reproducibility with intra-class coefficients of inter- and intra-observers of 0.96 and 0.95 respectively. Moreover, validation studies of this classification observed a very good reproducibility [33].

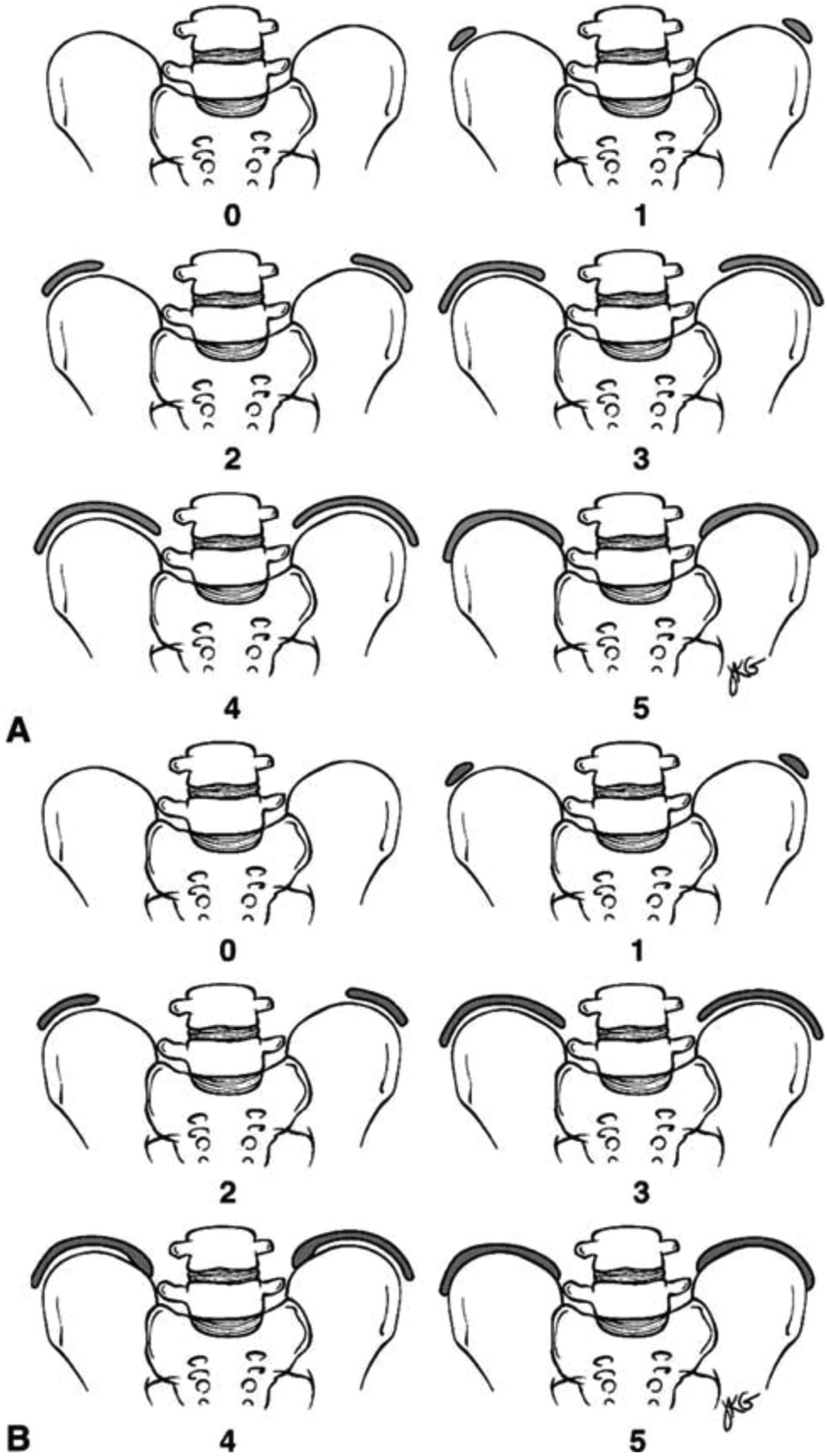

Fig. 6. The illustrations show the United States and French Risser grading systems. (A) The United States system has 6 grades: Risser 0 (no ossification), Risser 1–4 (ossification in quarters), and Risser 5 (fusion of the apophysis). (B) The French system also has 6 grades: Risser 0 (no ossification), Risser 1–3 (ossification in thirds), and Risser 4–5 (fusion of the apophysis).

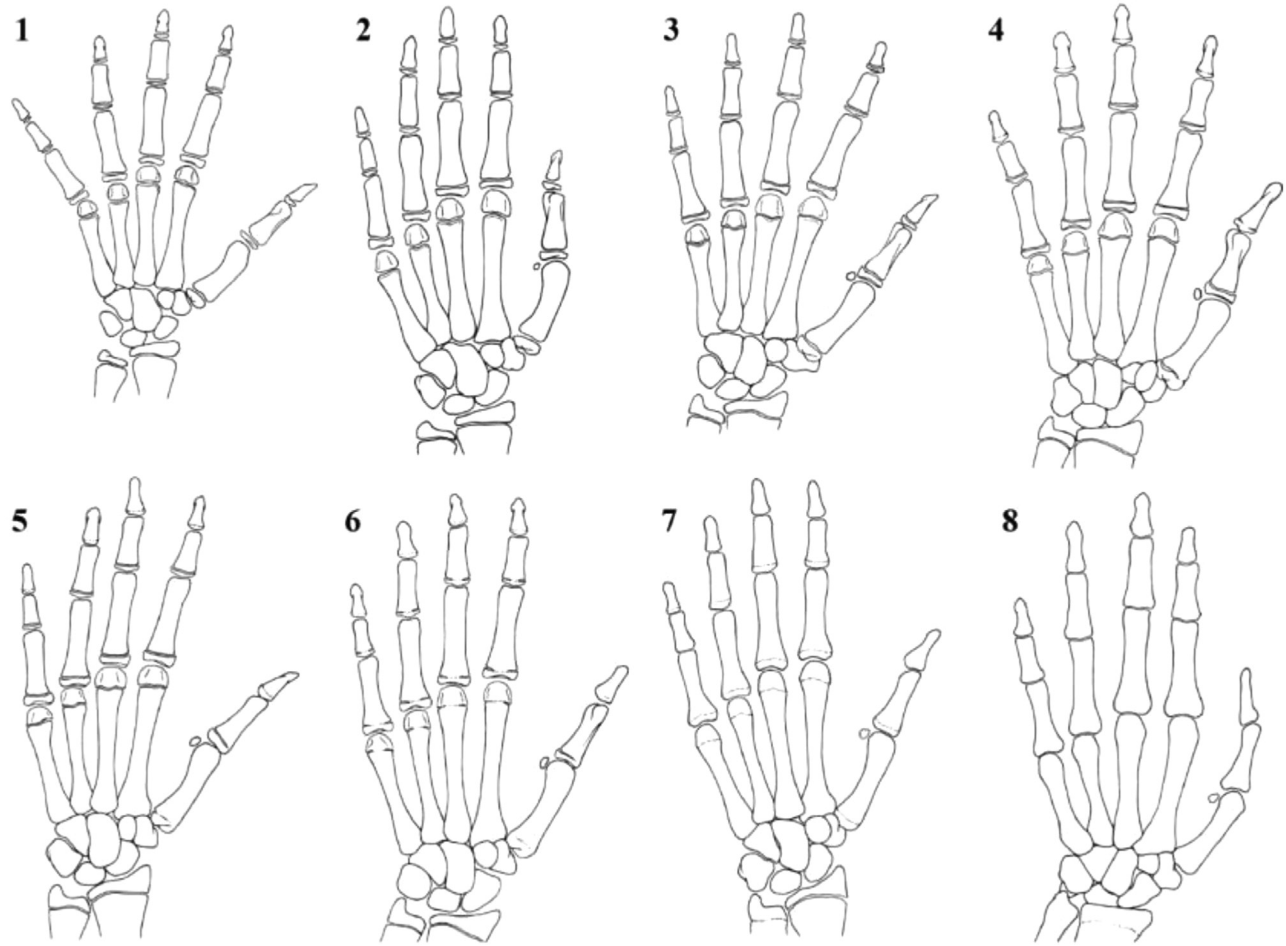

Fig. 7. Sanders Maturity Stage (SMS).

Clinical application

Peak height velocity

In clinical practice, PHV begins at Risser 0, Tanner 1 (breast appearance) and Sanders 2 with open triradiate cartilage and digital uncapped phalangeal epiphyses. PHV ends after Risser 4, Tanner 3 (breast and pubic hairs) and Sanders 7 with closed triradiate cartilage and fused digital epiphyses. So, we need to consider starting bracing at Risser 0 if the curve is greater than 20°.

Curve acceleration phase

Assessing spinal growth and regular follow-up of patients is interesting to determine the occurrence of the curve acceleration phase (CAP). It is a rapid change in curve progression in early adolescence. Before the CAP, curve progression averages 0.2° per month and is close to 1.0° to 2.0° per month just after the CAP begins. Authors observed that increasing curves had similar periods of rapid worsening, with different chronological ages [7].

Thus, patients who are the most skeletally immature when scoliosis is diagnosed are at the greatest risk of having a curve progression, as initially demonstrated by Me Duval-Beaupère [12]. Nevertheless, the growth spurt period and the CAP does not necessarily coincide, as demonstrated by Cheng et al. that observed that the maximum scoliosis worsening occurs just after the growth peak [34]. Lee et al. showed that patients with a Cobb angle inferior to 18° had less risk of progression [35]. Similarly, Sitoula et al. demonstrated that patients with curves of less than 20° and SMS 3 progress rarely [15].

The sanders maturation system shows 4 main periods of scoliosis progression: the infantile-rapid, the juvenile-slow, the adolescent-rapid and the mature-slow. During the juvenile and preadolescence slow phases, the curves are at little risk of progression [7]. Thus, SMS can be a useful prognostic reference point for the effectiveness of a brace and the risk for crankshaft phenomenon. The other advantage is that SMS is available before Risser 0, closure of the triradiate cartilage, PHV and Tanner 2, and will therefore provide a better prediction of maturity than these other parameters.

Remaining growth and maturation assessment are particularly important for certain surgical techniques such as the vertebral body tethering (VBT), based on growth modulation: the more the patient is skeletally immature, the more a successful correction might be expected after the VBT, which however depends on the initial severity of the curve [36,37]. Thus, SMS 2 patients will have more scoliosis corrections than those SMS 3 and are even at risk of hyper correction and complication. Consequently, SMS 3 and 4 patients are considered more suitable for VBT treatment [38]. On the other hand, very little growth modulation and therefore curvature correction is expected for SMS 4 or 5 patients [37].

Maturity

Maturity is acquired at Risser 5 and SMS 8 when all epiphyses are closed, and without any residual changes for the sitting and the standing

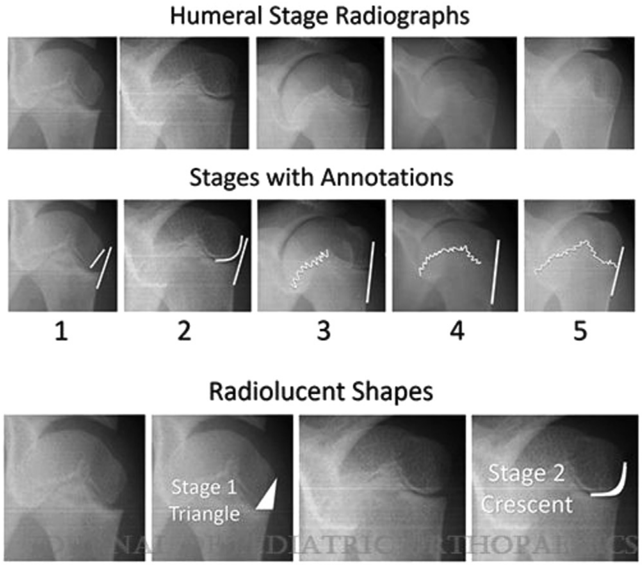

Fig. 8. Proximal humerus ossification classification. Stage 1 demonstrates an incompletely ossified lateral epiphysis leaving a triangular area of radiolucency on the lateral aspect of the epiphysis. Stage 2 demonstrates increased ossification of the lateral epiphysis leaving a crescent shaped area of radiolucency on the lateral side of the epiphysis. These shapes are highlighted below the annotations with representative images shown both unmodified and with the shapes superimposed. Note that in stages 1 and 2, the black line parallel to the lateral metaphysis does not touch the epiphysis. Stages 3 through 5 all demonstrate colinearity between the lateral margin of the epiphysis and the metaphysis. In Stage 3, the lateral half of the physis is open without obvious fusion. In stage 4, the lateral half of the physis thins and begins partial fusion. Finally, by stage 5 the lateral half of the physis demonstrates essentially complete fusion. The same annotations used on the schematic are superimposed upon the radiographic examples for ease of comparison.

trunk height. This is the time when we can consider stopping a brace treatment in SI.

Evolution of spinal sagittal alignment changes during childhood

Regarding sagittal alignment, the literature is consistent in its observations of parameters evolution. Variations between studies are minor, mainly relating to the magnitude of changes rather than their direction or clinical significance.

Sacro-pelvic parameters

Pelvic incidence

Numerous studies consistently report that PI increases with growth [39–42]. Mean values typically range from 40 to 43° in young children to approximately 46° in adolescents, stabilizing in adulthood. This increase is especially noticeable at the onset of puberty (PI in children aged 3–10 years is 43.7° ± 9.0°, in adolescents aged 10–18 years it is 46.9° ± 11.4°, and it remains stable after growth in adults) [39,41].

Pelvic tilt

Pelvic tilt (PT) also increases during growth, rising from 4° to 5° in children to 7-9° in adolescents. These changes are statistically significant, particularly during puberty. Mac-Thiong et al. reported that PT in children aged 3–10 years is 5.5° ± 7.6° and in adolescents aged 10–18 years it is 7.7° ± 8.3° [39]. Similarly, Pesenti et al. found that pelvic tilt increased from 4° to 9° during growth [41]. This increase in PT is correlated with the PI growth.

Sacral slope

Unlike pelvic incidence (PI) and pelvic tilt, sacral slope (SS) remains relatively constant throughout growth, with values around 38–39° (SS in children aged 3–10 years is 38.2° ± 7.7°, and in adolescents aged 10–8 years it is 39.1° ± 7.6°) [39,41].

Spinal local parameters

Lumbar lordosis

Lumbar lordosis (L1-S1) increases significantly with age, ranging from 42° to 53° in young children to approximately 46° to 56° in adolescents. The most notable changes occur during the second phase of the pubertal growth spurt. This increase is consistently reported, though there is some variation in normative values. Abelin-Genevois et al. found LL to be 42.5° ± 9° before the age of 10 years-old and 46.7° ± 7° between 11 and 18 years-old [40]. Mac-Thiong et al. reported that mean LL is 53.8° ± 12.0° in children aged from 3 to 10 years and 57.7° ± 11.1° in adolescents aged from 10 to 18 years, with similar values in adults [39]. Pesenti et al. observed an increase in LL from 51° to 56° ($p<.001$) [41].

Thoracic kyphosis

Thoracic kyphosis (TK) (complete kyphotic segment) shows a slight increase with growth, from 39° to 42° in young children and from 41° to 45° in adolescents. The variations are more subtle compared to lumbar lordosis and are particularly marked during the deceleration of the pubertal growth spurt. Mac-Thiong et al. reported mean TK as 42.0° ± 10.6° in children aged 3–10 years and 45.8° ± 10.4° in adolescents aged 10–18 years, with a slight tendency to increase in adults with age [39]. Pesenti et al. found that TK slightly increased from 39° to 41° ($p=.005$) [41].

Cervical lordosis

Cervical lordosis evolves significantly during growth to adapt to the changing alignment of the spine and the head's position. Abelin-Genevois et al. found that while the overall C1-C7 cervical lordosis remains relatively stable from childhood to adolescence, there are significant variations in the subaxial cervical spine (C2-C7) [43]. Indeed, C2-C7 cervical lordosis angle significantly changes during growth, with values decreasing from an average of –6.5° in children under 10 to –0.7° in adolescents aged 11–18 years-old. In children under 10 years old, the cervical spine tends to have a more lordotic curve which gradually adjusts with age to ensure a global harmony with the thoracic kyphosis and the horizontal gaze.

Spinal global alignment

The center of gravity shifts backward with age, reflecting progressive postural maturation [39–42]. In the growing child, posture becomes more upright, followed by a tendency towards kyphosis in adulthood. Mac-Thiong et al. found that the C7 plumbline tends to move backward with age [39]. The C7-plumbline is anterior in children (3–10 years old), adolescents (10–18 years old) and adults (>18 years-old) in respectively 28.7%, 12% and 14.1% of the cases. After, it stabilizes or slightly moves forward due to aging and degenerative changes

Surgical strategies related to growth modulation

Different techniques exist to treat spinal pathologies in children. These include growth modulation techniques before skeletal maturity and correction-fusion after this maturity, particularly in cases of severe deformity (Fig. 9). The growth modulation techniques aim to correct

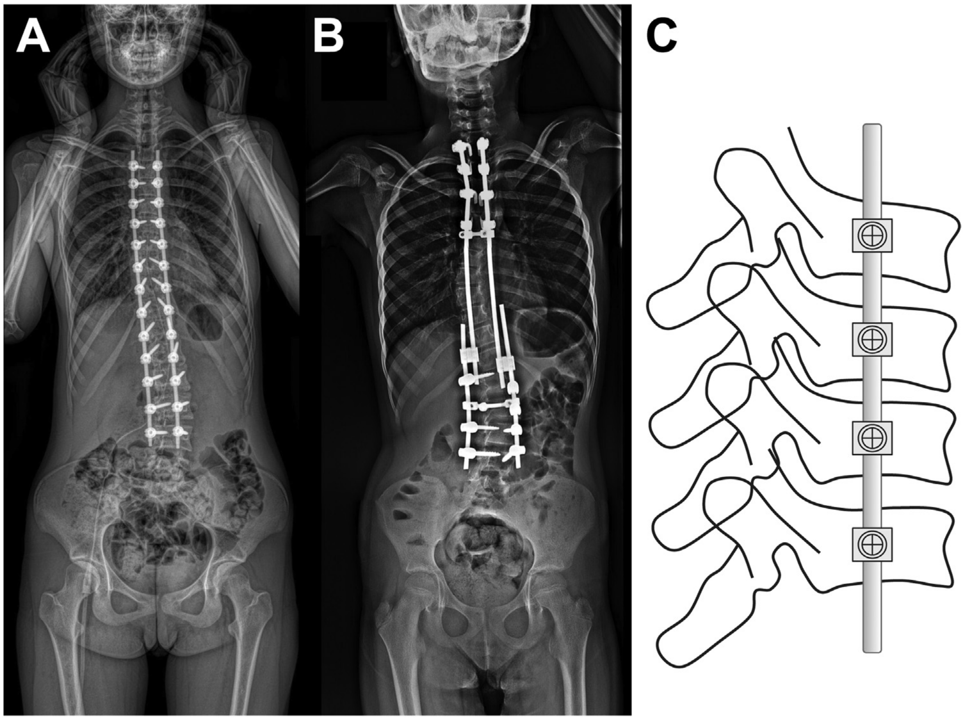

Fig. 9. Radiographs of traditional posterior fusion (A), dual growing rods technique (B) and diagram of vertebral body tethering (C).

deformities while allowing for continued growth and development of the spine.

Growing rods

The challenge in treating early-onset scoliosis (EOS, i.e. deformity that is present before 10 years old) is to prevent the worsening of the deformity, or even correct it, while allowing for the development of the spine and thoracic cage. This is essential for the overall growth and lung development of the child. Among the growth-friendly techniques, growing rods are the most frequently used.

Growing rods are indicated for use in cases of progressive spinal deformity before the PHV, particularly when orthopedic treatments such as bracing or casting have proven ineffective. Several techniques were developed. A single rod was used originally, which was periodically lengthened through surgery to accommodate the child's growth [44,45]. It used to be the standard growth modulation treatment for pediatric deformity, but required multiple surgeries. A definitive posterior spinal fusion (PSF) would eventually be carried on, when skeletal maturity was obtained, to preserve the correction over the long term. The addition of a second rod was progressively recommended to strengthen the construct [46,47]. Modern instrumentations were developed with magnetic expandable rods, using a magnetic remote control to lengthen the rods, thus reducing the need for reoperations [48]. Fusion is performed at skeletal maturity to complete the correction and achieve a solid, stable fusion over time. However, some teams debate the necessity of this final posterior fusion, relying on the spinal ankylosis that is often achieved through the various retention surgeries [46]. In a study by Bouthors et al., involving 34 children treated with traditional single growing rods, there was no significant difference in radiological parameters between the group that underwent posterior spinal fusion (PSF) at skeletal maturity and the group that did not (nonfusion treatment relying on spinal ankylosis) [46].

The main limitations of growing rods are the need of periodic surgeries to lengthen the rods if a traditional rod is used, and the risk of rod breakage, especially when a single rod is used. Dual rods are strongly recommended to prevent fractures and maintain correction stability.

Vertebral body tethering

Vertebral body tethering (VBT) is a growth modulation technique used for AIS, aiming to correct scoliosis while preserving spinal flexibility. Through thoracoscopy, screws are placed laterally along the convex side of the spinal curve, which are then connected by a flexible tether. The tether is tensioned to correct the scoliosis partially at the time of surgery. As the patient grows, the tension on the tether helps to guide the spine into a better coronal alignment, leveraging the body's natural growth process to achieve further correction over time.

The main advantage of VBT is the preservation of spinal flexibility. Wong et al. conducted a systematic review to compare the range of motion (ROM) outcomes between VBT and PSF in treating AIS [49]. The review found that VBT offers superior motion preservation outcomes compared to PSF.

Compared to the classical risks associated with PSF, VBT presents 2 specific complications: overcorrection and distal adding-on [49]. Overcorrection occurs when the scoliosis curve is corrected too much, causing the spine to curve in the opposite direction [50]. This can happen if the tether is too tight or if the child's growth rate is underestimated, potentially leading to a new spinal deformity. Distal adding-on refers to the progression of the curvature beyond the tethered segments, extending further down the spine [49]. These 2 complications may warrant possible conversion surgery to PSF.

To limit these complications, Wong et al. emphasized that careful patient selection is crucial [49]. Yet, the selection criteria are still a subject of debate; patients should not be too skeletally mature, but also not too young, to avoid the risk of overcorrection. They should present with moderate scoliosis curves (30°–50°) that are flexible on bending radiographs, and have significant remaining growth potential. Additionally, those with severe rotational deformity or very rigid curves are less suitable for VBT due to a higher risk of complications . This raises the question of whether these patients might be better candidates for bracing rather than risking thoracoscopy.

Thus, several studies highlight the need for individualized treatment planning based on specific patient characteristics and growth potential . According to Alfraihat et al., machine learning models can predict radiographic outcomes of VBT, providing individualized predictions for surgical success [51].

Conclusion

Understanding the evolution of spinal sagittal alignment during childhood and adolescence is crucial for managing musculoskeletal disorders in this population. The study highlights that key parameters such as PI, PT and LL increase significantly with growth, particularly during the pubertal growth spurt, while SS remains relatively constant. Additionally, there is a posterior shift in the center of gravity as children grow, reflecting progressive postural maturation.

These changes underscore the importance of early and accurate assessment of skeletal maturity to predict and manage conditions like adolescent idiopathic scoliosis (AIS). The development of reliable maturity classification systems, such as the SMS and Tanner-Whitehouse III, enhances our ability to tailor treatments to individual growth patterns.

The integration of these systems into clinical practice allows for more precise prediction of curve progression and the timely application of therapeutic interventions, ranging from bracing to surgical options like growing rods or vertebral body tethering (VBT), since growth modulation is a key factor in successful outcomes.

Declaration of competing interests

One or more of the authors declare financial or professional relationships on ICMJE-NASSJ disclosure forms.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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